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REVIEW ARTICLE

Delayed Controlled Atmosphere Storage Related to the Development of Internal Storage Disorders in Apples and Pears: A Review

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Abstract
The delay in the establishment of the controlled atmosphere (CA) conditions has been shown to be an effective storage procedure in alleviating or even preventing the occurrence of internal storage disorders (ISD) in apples and pears during long-term CA storage. Apples and pears respond differently to this practice in relation to the prevention of ISD during long-term CA storage and/or in keeping quality traits such as flesh firmness, soluble solids, acidity and skin color. Therefore, the responsiveness of these pome fruits varies either in relation to the effectiveness in alleviating the occurrence of ISD or regarding the exposition time of fruit in air at low temperature before long-term CA storage. This review aims to discuss everything from the initial experimental trials using this procedure with apple and pear to the current results and commercial application for the storage of pears. The possible mode of action of delayed CA in reducing the occurrence of ISD in apples and pears as well as the benefits of the rapid CA (secondarily) is also discussed.

Keywords Low temperature pre-conditioning · Fruit quality · *Malus domestica* · Physiological disorders · *Pyrus communis*

Introduction

World fruit production recorded a growth of 63% from 2000 to 2022 with a total production volume in 2022 of 933 million tonnes (FAO 2023). After bananas and watermelons, apples are the third most produced fruit worldwide with 96 million tonnes (FAO 2023). Despite having lower world production, pears accounted for 26 million tonnes, making the two pome fruits most important worldwide together with apples (FAO 2023).

Both apples and pears show this high worldwide production mainly due to their good taste, high nutritional value and the ability for long-term storage, either under air at low temperature or under controlled atmosphere (CA) storage (static or dynamic CA). In general, apples and pears show high suitability for long-term CA storage, but both exhibit variability between cultivars regarding susceptibility to the occurrence of internal storage disorders (ISD) during long-term CA storage. In general, pears are more susceptible to the development of ISD than apples, although some pear cultivars have been shown to be very tolerant to long-term CA storage when pre-conditioned in air at low temperature before the establishment of CA conditions. This duration time of delayed CA and the temperature of exposition vary among the cultivar and specie when comparing pears with apples. However, above all, the procedure has been shown to be effective either for apples in alleviating or even preventing the development of ISD during further long-term CA storage. In many cases, such as the pear cultivar 'Conference' in Europe, the procedure is applied in commercial storage rooms as a standard protocol[1] .

Traditionally, since the discovery of the CA storage, the most common and advisable recommendation for better and longer storage of fruits is the rapid cooling and rapid establishment of CA conditions. However, during the last 30 years, storage protocols have been changing, not so much in air under low temperature (cold storage), where rapid cooling is always fundamental, but mainly under CA storage (static or dynamic CA); then, at the end of the 1990s, Swiss researchers published the first investigation about the effectiveness of delayed CA in reducing the in-

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cidence of ISD in 'Conference' pear (Höhn et al. 1996). The authors observed a reduction in cavity formation by 50–90% in 'Conference' pear, depending on orchard region, when the CA regime was delayed by 21 days, during which fruits were kept only in air at low temperature. This was the first investigation with pears showing the benefits of this practice, which will be described and discussed in detail below.

Delayed Establishment of CA Conditions: The Procedure

Delayed pull down in oxygen partial pressure (pO_2) or delayed CA storage is a practice in which fruit are maintained under air at low temperature (temperature adjustable according to the specie and/or cultivar) for a variable period at the beginning of storage, before the CA regime is established. This practice contrasts with rapid CA storage, in which the pull down in pO_2 starts immediately after the fruit are cooled. As reported before, the procedure was investigated in pear by Höhn et al. (1996), who published the first results about the benefits of delayed CA in reducing the occurrence of ISD in 'Conference' pear. Höhn et al. (1996) observed a reduction in cavity formation by 50–90% in 'Conference' pear, depending on orchard region, when the CA regime was delayed by 21 days. This was the pioneer work with pear and testing 21 days of delay CA, but in the following discussion, we will see more situations for apples and pears depending on country and/or region, cultivars and CA conditions.

Delayed CA Storage for Pears

After the first investigation carried out by Höhn et al. (1996), the beneficial effect of CA delayed by 21 days in reducing ISD in 'Conference' pear, it was subsequently confirmed during other studies with the same pear cultivar (Roelofs and de Jager 1997; Saquet et al. 2001, 2003a, 2003; Verlinden et al. 2002). However, depending on pear cultivar, maturity at harvest, location and CA conditions, the time in air at low temperature before the establishment of CA conditions can change. For 'Conference' pear, the 21-day CA delay seems to be the optimum for further long-term CA storage. Further, the practice has been used as a standard commercial protocol for successful long-term CA storage of 'Conference' pear in Europe.

The procedure was tested with other pear cultivars, which are susceptible to ISD during long-term CA storage, but not as much as 'Conference'. For some pear cultivars such as 'Rocha', delayed pull down of pO_2 for 46 days reduced ISD in fruit at 3.0 kPa O_2 to 35.5%, but increased disorder incidence in fruit at 0.5 kPa O_2 to 27.3% (Saquet et al. 2017). The effect of delayed CA on ISD depended on pO_2, and delaying CA for 46 days did not benefit 'Rocha' pear during long-term storage (Saquet et al. 2017). A 4-week CA delay reduced the occurrence of the storage disorders in 'CH 201' pear cultivar grown in Switzerland, compared to a 2-week delay or the rapid establishment of CA conditions (Rebeaud et al. 2024). For 'Rocha' pear, it was defined at the same time that the rapid CA under very low pO_2 such as 0.5 kPa was the best storage condition after 8.5 months of static CA storage (Saquet 2017; Saquet et al. 2019). Perhaps, if the 21-day CA delay had been tested, the procedure could offer some benefits in reducing the ISD in 'Rocha' pear.

Delayed CA Storage for Apples

It is very likely that the first investigation that mentions the CA delay in apples was developed by Anderson and Abbott (1975), but without investigating the occurrence of ISD during storage. The authors' main conclusion was that the 90-day delay of CA did not maintain fruit quality as well as regular CA and not much better than storage in air; better results in their trial were verified using the rapid establishment of the CA conditions with the cultivars 'Golden Delicious', 'Delicious', 'Rome Beauty' and 'Stayman Winesap'. The cultivar 'Bramley's Seedling' showed promising results when 15-day CA delay was tested (Colgan et al. 1999). Delaying establishment of CA conditions for 2–12 weeks significantly reduced the severity of CO_2 injury in 'Fuji' apple (Argenta et al. 2000). 'Elstar' apple subjected to 30-day CA delay significantly reduced the occurrence of ISD; however, fruit showed lower firmness and lower acidity (Streif and Saquet 2003). Delaying CA storage for 30 or 60 days reduced external CO_2 injury and flesh browning in 'Empire' apple (DeEll and Ehsani-Moghaddam 2012). The response of 'Braeburn' apple is frequently reported when fruit are kept in air at temperatures near 0 °C for 14 days (Elgar et al. 1998) or 21 days (Saquet et al. 2003b; Neuwald et al. 2014; Hatoum et al. 2014). According to De Castro et al. (2008), delayed CA for 30 days reduced the occurrence of flesh browning in 'Pink Lady' apple after 6 months of storage. 'Honeycrisp' apple was held in air at 3 °C for 0, 2, 4, 8, or 14 weeks, followed by CA storage (3 kPa O_2 and 1.5 kPa CO_2) at 3 °C for 6–7 months of storage. Delaying the establishment of CA conditions reduced the occurrence of internal CO_2 injury, with or without flesh cavities (DeEll et al. 2016). The apple cultivar 'Cox Orange Pippin' subjected to delayed CA did not keep satisfactory fruit quality traits, and still resulted in high watercore and ISD at the end of storage (Saquet 2020).

After many reports about the benefits of delayed CA in reducing or even preventing the occurrence of ISD in susceptible apple cultivars before long-term CA storage, it is advisable to report on the risks of this procedure regarding the possible loss of fruit quality traits in some apple cultivars. Such apple cultivars do not need the use of this practice because they are not susceptible to ISD and rapid CA is advisable. Smock and Blanpied (1963), in one of the first investigations with the cultivar 'McIntosh', showed losses in firmness and acidity when a 14-day delay was tested. The cultivar 'Golden Delicious' showed higher losses in firmness and acidity when the establishment of CA conditions was delayed (Lau and Looney 1982). Later, Liu (1986) confirmed this need of 'McIntosh' for rapid CA storage in order to keep higher fruit quality. Brackmann and Saquet (1999), investigating the storability of 'Gala' apple, concluded that rapid CA and low ethylene prolong storage period with better fruit quality. 'Jonagold' apple is another very tolerant apple cultivar to extremely low pO_2 and high pCO_2 which responds positively to the rapid establishment of CA conditions while keeping high fruit quality without developing ISD (Saquet 2016).

On the Possible Mode of Action of Delayed CA in Reducing ISD in Apples and Pears

The physiological and biochemical mode of action underlying the benefits of delayed CA in reducing ISD have been investigated in 'Conference' pear, but not very extensively. Compared with rapid CA, fruit of 'Conference' stored under delayed CA (21 days in air at 0 °C) showed higher ethylene production, higher respiration rate, and higher adenylate energy charge (AEC) during the first 3 months (Saquet et al. 2001), as well as maintaining higher concentrations of oleic, linoleic, and linolenic fatty acids of membranes during the initial storage period in air (Saquet et al. 2003a). Higher AEC and better maintenance of membrane integrity were the proposed mechanisms to explain, at least in part, the effect of delayed CA on the reduction of ISD in pear and apple fruits (Saquet et al. 2001, 2003a, b). After 4 months of storage, 'Pink Lady' apple subjected to delayed CA showed greater conservation of ascorbic acid and reduced occurrence of flesh browning. In addition, apples in air storage can show increases in intercellular volume (Ruess and Stösser 1993), and these changes could also help fruit adapt to CA conditions by increasing gas exchange within the cortex and core tissues (McCormick et al. 2021).

Not much research has been found that attempts to clarify the possible mechanism of this 'adaptation' during the pre-conditioning of pear and apple fruits prior to the establishment of CA conditions; this is a necessary field of research to also better establish the optimal time (days or weeks) of delaying CA and the temperature for apples and pears as well as to study the possibility of the use of this procedure for other fruits.

General Discussion and Concluding Remarks

After gathering this information addressing and comparing data in favor of delayed CA or in favor of rapid CA, we can discuss as follows: The need for rapid cooling is common to both apples and pears. Rapid cooling slows down fruit metabolism very rapidly and effectively. This practice is fundamental to keeping fruit quality during storage, either under air or under static CA or dynamic CA of apples and pears.

In relation to the use or not of delayed CA, some pear cultivars are very suitable for the rapid establishment of CA conditions, while others depend on delayed CA to achieve successful long-term storage. Among the most studied pear cultivars, 'Conference' is the main pear cultivated in Europe and is also highly dependent on delayed CA before further long-term CA storage to prevent the occurrence of ISD; the 21 days of delayed CA for 'Conference' is well defined. Otherwise, 'Rocha' pear has been shown to behave differently and can be stored for up to 9 months using rapid establishment of CA atmospheres, although its storage protocols have not yet been definitively investigated. There are other very important pear cultivars around the world, but for these it was not possible to find literature studying the effectiveness of delayed CA. Some examples of these pear cultivars include 'Bartlett' (or 'Williams'), 'D'Anjou', 'Passe Crassane', 'Comice', 'Abbé Fettel' and 'Alexander Lucas'.

A similar dependence on the rapid establishment of CA conditions can be observed in various apple cultivars, which need a delay in CA establishment in order to prolong the storage time, keep better fruit quality and reduce the occurrence of ISD. 'Fuji' and 'Braeburn' are typical cultivars which respond positively to a delay in CA in terms of reducing the occurrence of ISD without significant losses in quality traits such as firmness, acidity and skin color. On the other hand, 'Jonadold' and 'Golden Delicious' are cultivars that are very tolerant to rapid CA establishment, keeping very good quality without the occurrence of ISD when subjected to rapid CA.

As shown earlier, rapid cooling is common for apples and pears in this discussion, prior to the establishment of CA atmospheres, but whether rapid CA or delayed CA is needed is another question that requires critical analysis/knowledge by the storage managers, taking into consideration the pear or apple cultivar and their respective characteristics and requirements in terms of temperature and pO_2 and/or pCO_2 during subsequent CA storage.

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